Results from the PALM-3000 high-order adaptive optics system

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ABSTRACT

The first of a new generation of high actuator density AO systems developed for large telescopes, PALM-3000 is optimized for high-contrast exoplanet science but will support operation with natural guide stars as faint as V ~ 18. PALM-3000 began commissioning in June 2011 on the Palomar 200" telescope and has to date over 60 nights of observing. The AO system consists of two Xinetics deformable mirrors, one with 66 by 66 actuators and another with 21 by 21 actuators, a Shack-Hartman WFS with four pupil sampling modes (ranging from 64 to 8 samples across the pupil), and a full vector matrix multiply real-time system capable of running at 2KHz frame rates. We present the details of the completed system, and initial results. Operating at 2 kHz with 8.3cm pupil sampling on-sky, we have achieved a K-band Strehl ratio as high as 84% in ~1.0 arcsecond visible seeing.

Keywords: Adaptive Optics, Palomar, PALM-3000

1. INTRODUCTION

The Palomar Adaptive Optics (PALAO) system has since its inception been at the forefront of adaptive optics (AO) technology and has been used both for interesting scientific discoveries[1] and to test innovative technology. With the test of the well-corrected subaperture on the PALAO system[2], it was shown that the AO system on the Hale 200" telescope could work well in the high-contrast regime. PALM-3000 is an extension of that extreme AO concept to the full telescope aperture and is the first of a new generation of such AO systems for large telescopes to make observations on-sky. The PALM-3000 system, along with its suite of scientific instruments, offers the exciting possibility of directly imaging extrasolar planets and allowing the detailed study of their surfaces and atmospheres.

Several science instruments have been created to utilize the correction provided by the PALM-3000 system, each addressing different scientific goals. Already in use with the PALM-3000 system, are the PHARO infrared camera and spectrograph which provides imaging and grism spectroscopy at 0.96-2.5 µm wavelength over a 25-40 arcsec field[3], the P1640 coronagraphic integral field spectrograph (IFS) built by the American Museum of Natural History with a post-coronagraphic calibration wavefront sensor contributed by JPL which provides spectra over 1.1-1.65 µm wavelengths for a 10 arcsec field[4], the O-SWIFT I-z band integral field spectrograph which provides spectra over 0.6-1 µm wavelengths for a 4 arcsec field[5], and the Fiber Nuller high-contrast coronagraphic imager built by JPL which provides images at 1.4-2.2 µm[6]. In addition, a new visible imager from Caltech, TMAS[7], will be commissioned in fall of 2012 and a calibration system for the PHARO instrument is planned in 2013 to improve contrasts using novel coronagraphic techniques such as the vector vortex[8].

One of the primary science goals of the PALM-3000 AO system is to detect and characterize extrasolar planets. To achieve this goal, the PALM-3000 system was designed to correct down to an RMS residual wavefront error of 105 nm on a bright star in median atmospheric conditions – equivalent to a Strehl ratio of 85% in H band (1.64 µm wavelength). At these low wavefront errors, using the P1640 instrument, we expect to reach contrast levels of 10^{-5} at 0.4" separations and 10^{-7} at 1.0" separations from bright stars, post-processing.

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The PALM-3000 project[10] is an upgrade to the successful PALMAO system used for more than 10 years at Cassegrain focus of the 5.1 meter Hale Telescope at Palomar Observatory[9]. This paper presents an update on the commissioning of the system and initial on-sky performance.

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2. SYSTEM DESCRIPTION

The PALM-3000 upgrade reused many of the components of the previous Palomar AO system, including the optical bench and telescope mounting interface, 350-actuator deformable mirror, large optics, internal source, and handling equipment. The new components are the 3388-actuator deformable mirror, a Shack-Hartmann wavefront sensor (WFS) with up to 64x64 sampling in the pupil plane, and a new wavefront reconstructor computer system. The design and testing of these new components has been described previously[11][12][13].

2.1 Hardware

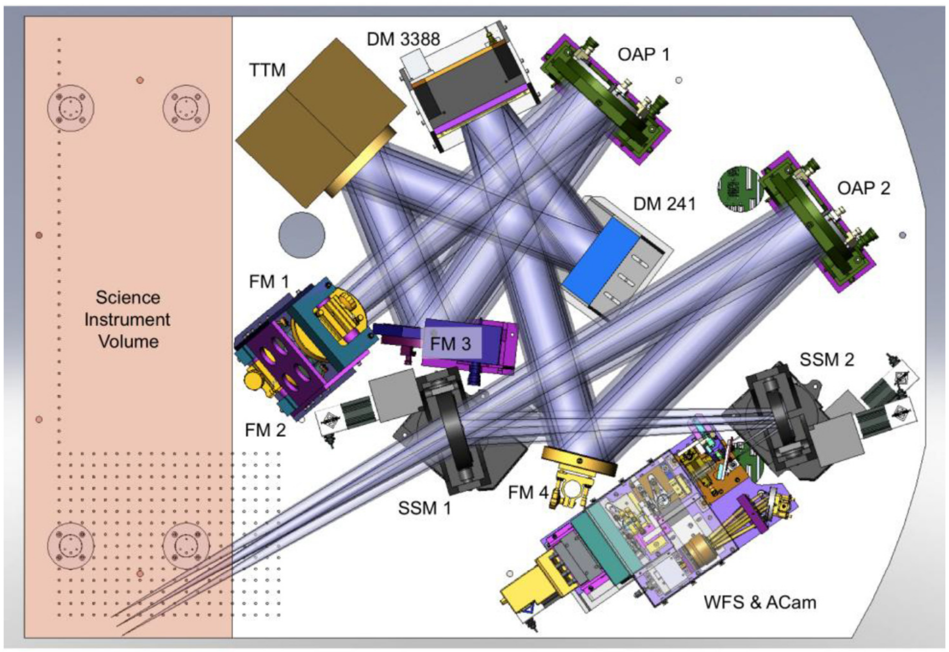

Figure 1 AO system layout

A single optical relay reimages the telescope pupil to the high-order deformable mirror (HODM) in collimated space. The low-order deformable mirror (LODM) and the fast steering mirror (FSM) are in the collimated space conjugate to 700m above the telescope and 2200m above the telescope, respectively. Two steering mirrors are used to align image and pupil on the wavefront sensor (WFS). The science light is split at the first of these steering optics using a dichroic to send visible light to the WFS and transmitting visible through near infrared (NIR) light to the science instrument. The bandpass available to the science instrument can be adjusted by changing the dichroic.

The wavefront is measured using a Shack-Hartmann sensor with four possible lenslet arrays that give 64, 32, 16, and 8 samples across the pupil, corresponding to subaperture sizes of 8cm, 16cm, 32cm and 64cm on the sky. The lenslet arrays are on a motor-controlled, x-y stage setup that allows for both changing the array and fine adjustment of the field stop/lenslet/detector alignment.

2.2 Wavefront Control

Wavefront control is accomplished by full vector matrix multiply (VMM) in 16 NVIDIA graphics processing units (GPUs) installed in 8 PCs. A fast switch (Quadrics) provides communications between the PCs to achieve the required latency to run the system at frame rates up to 2000Hz. The camera frame rates are continuously variable form 30Hz to 2000Hz which allows the system to provide correction on fainter stars without reducing the sampling on the WFS. The WFS has four sampling modes implemented optically, although only three of these modes have been implemented in the real-time control algorithms (RTC). The primary uses of the system require either very good wavefront correction on bright objects, such as the 100-150nm residual wavefront error which is achievable in 64x and 32x modes, or modest correction on faint objects, such as the 400-500nm residual wavefront error which is achievable in 8x mode. Due to this, the focus has been on optimizing these three modes rather than implementing the additional 16x mode.

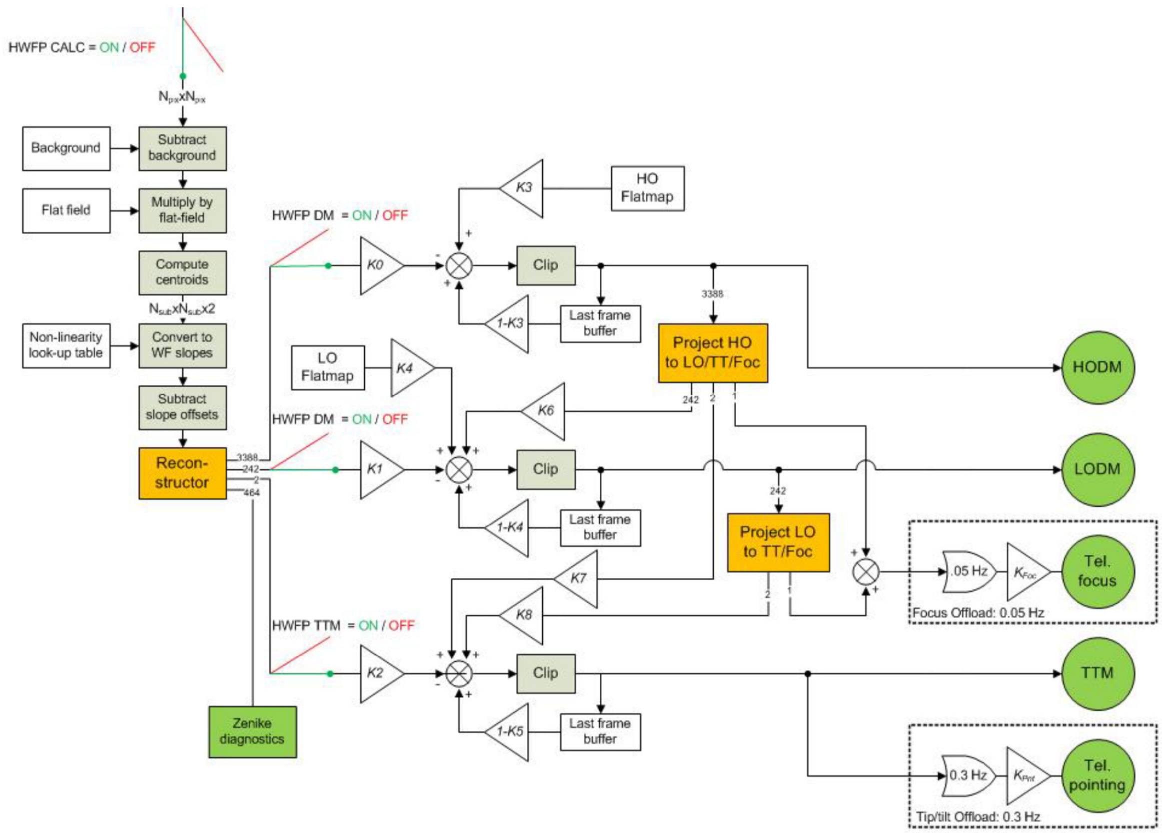

Figure 2 Servo Control Flow Diagram

In order to provide maximum flexibility in the servo loop control, there are two primary loops implemented around the active mirrors: one around the deformable mirrors and one around the fast steering mirror. The loops include proportional and integral terms as well as the option of offloading from one mirror to another every frame. The RTC is currently functional as described here[15] and the goal of current work on the system is to understand the best way to use these controls.

2.3 Electronics and the Cassegrain Challenge

For such a complex system, a significant amount of electronic equipment is required to drive all the components. While some electronics, such as the RTC computers can be used remotely over fiber interfaces, many of the components require short cable runs to drive noise-sensitive and/or high voltage equipment. The WFS camera electronics, the drivers for both deformable mirrors and all the motor controllers must be local to the system. The HODM alone has 2 racks of driver electronics, 4 drivers in each, where each driver controls up to 480 actuators and dissipates 800W of energy.

The challenge of mounting the system at Cassegrain focus is multi-dimensional. In addition to challenges that were already understood, such as mounting of the optical bench and flexure within the system due to the changing gravity vector, there were the new challenges of removing the significant amount of heat dissipated by the new electronics and providing cabling for the several thousand wires running between the bench and the electronics that could be installed quickly and repeatably each time the instrument went on the telescope.

To remove the 6kW of heat generated by the electronics from their location directly under the primary mirror, a liquid cooling system was implemented. The system consists of cooled rack-mount trays of liquid piping and trays of fans to circulate air through closed racks. The system is run by a custom software interface and a Neslab chiller. Currently the cooling lines are run directly to the Cass cage across the floor of the telescope, which has the benefit of keeping all the cooling fluid below the level of the primary. The system has successfully removed the heat from the electronics. The PALM-3000 system now has a negligible effect on the temperature of the primary mirror and the electronics themselves are maintained at ambient temperature.

To provide robust, repeatable cabling for system, there are boxes for each major electronics system on the bench that combine the hundreds to thousands of wires into large cables with heavy-duty, military-style connectors. The box and cabling for the LODM was reused from the previous system, but the HODM and motor cabling required new designs. The HODM was delivered with ninety-nine small, delicate cables that bring the signal out from the back of the mirror. To map these over four thousand wires to sixteen 300-pin cables and then to the electronics drivers, we designed sets of identical boards and identical cables. The mapping of the wires to connectors on the boards however was done by hand, due to the complicated nature of the original electronics design and the box where this mapping is done is sealed. The motor cabling was done in a similar manner, and all the motors and power used on the bench were combined into two 250-pin cables. The results have been very robust and the installation time for the cabling is about an hour.

Figure 3 PALM-3000 installed at the Cassegrain focus of the Hale 200” telescope with the HODM cables in the foreground.

3. CURRENT PERFORMANCE

The PALM-3000 system was integrated and tested in the lab at Palomar Observatory from October 2010 through May 2010. The PALM-3000 system had first light in June 2011. To date we have achieved 150nm residual error on bright stars as measured in PHARO images, and 5×10^{-4} at 0.4” separations on Alcor measured in the P1640 instrument.

3.1 On Sky

There were two engineering runs in June and August 2011 before shared risk science began in October 2011. Initial performance numbers were promising in good Palomar seeing (~1 arcsec visible); however the performance goals were not achieved on bright guide stars. Performance in October and December in poor 1.5-2.5 arcsec seeing was considerably worse and some nights in November and December were lost altogether due to weather. A few nights on sky in April and May 2012 suffered from poor seeing (>2 arcsec visible), but reasonable correction under such conditions. In June 2012, one year after first light, good seeing allowed for a test of the current best performance of the system.

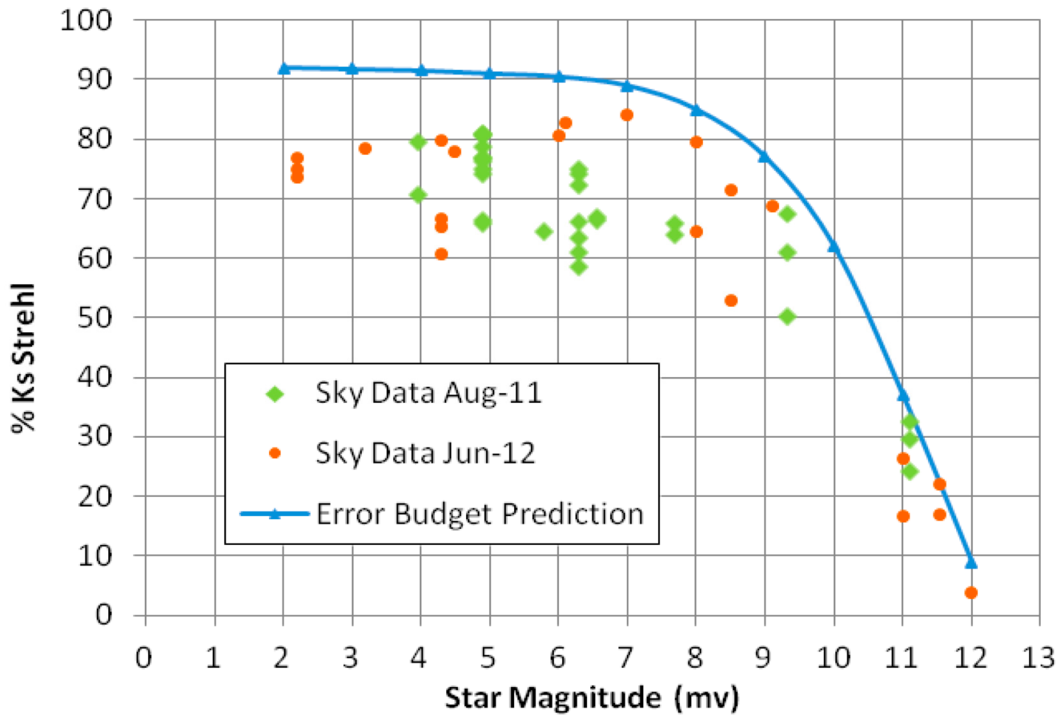

Figure 4 System performance on-sky in Ks in median seeing (0.7-1.2 arcsec visible), 64x mode only

The results for performance testing in median seeing for Palomar (1.1 arcsec, r0=9cm @550nm) show that there has been some improvement in the middle of the magnitude range for the 64x mode from August to June. Since the conditions for the two data sets were very similar, the improvement can be attributed improved reconstructors which include the affects of partially illuminated subapertures and improved understanding of appropriate loop gains. The results also show that the system is operating as expected at the faint end of the range, including the expected the limiting magnitude for the 64x mode.

For brighter stars, however, the results show a possible decrease in performance with flux. For the data points at 4th magnitude and brighter, the measurements were taken at a variety of frame rates and camera gains in order to test the effects of the WFS camera on the correction. The sample size is not large, but suggests that frame rate and flux in counts are not the primary reason for this decrease in performance. More testing is needed to verify this as there have been issues in the past with the electronics linearity of faster frame rates on the WFS camera.

The performance data was taken on F and G stars to remove the variable of star color for the test. However, there is an effect due to star color that has yet to be quantified. The effect is likely due to longitudinal color in the optical design of the 64x mode. Both quantification of the effect and potential mitigation are planned in the near future.

System performance in worse than marginal seeing is significantly reduced, but it is consistent with expectations. Ks Strehl ratios of 40-50% are routinely obtained in 1.5-2 arcsec visible seeing

All the results shown are for the 64x pupil-sampling mode. Performance in this mode is critical because this is the primary science mode for the system, to be used for both high-contrast NIR coronagraphy and visible science.

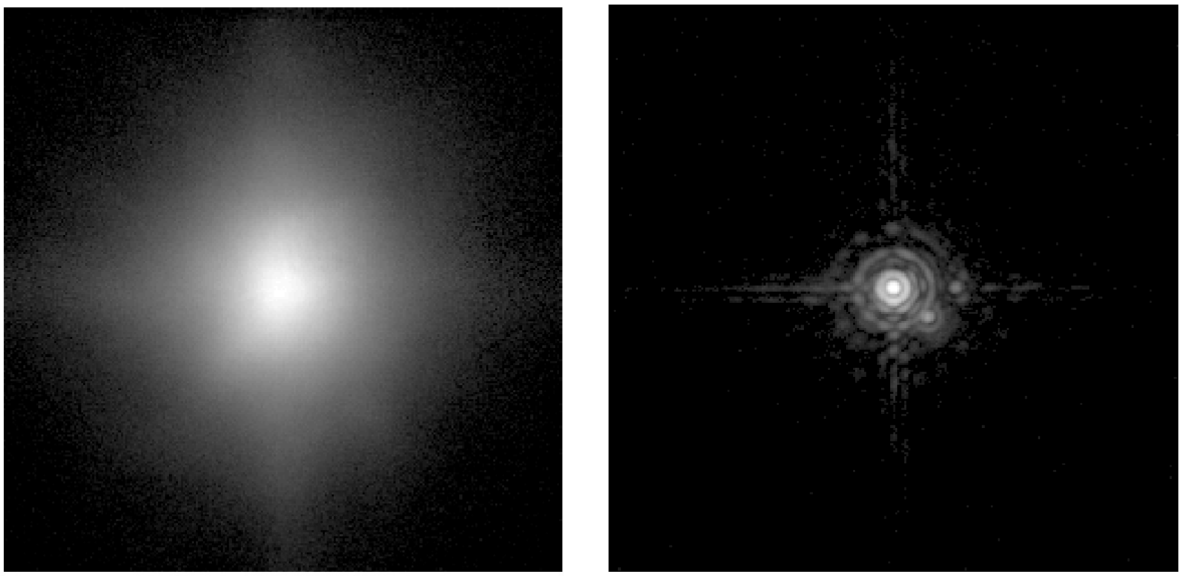

Figure 5 0.7 arcsec seeing, 2.5 minute integration; 80.6% Ks Strehl on mv=6.0, total integration time 2.2 min (96 frames), companion to the right at 0.7 arcsec, internal ghost from ND filter in the lower right

3.2 Non-Common Path Calibration

Calibration of non-common path WFE between the wavefront sensor and science instrument is accomplished using Modified Gerchberg Saxton phase retrieval directly on the science camera[14]. The error is iteratively measured and applied to the appropriate deformable mirror (low spatial frequencies are applied to the LODM and high-spatial frequencies are applied to the HODM), until a minimum error is achieved. The error is then measured in the WFS and the result is used as the reference centroids for closed loop operation.

The results below are typical. The problem areas on the HODM[13] are also visible, including the disconnected actuator on the center right and dimpled areas in the top left and along the lower edge.

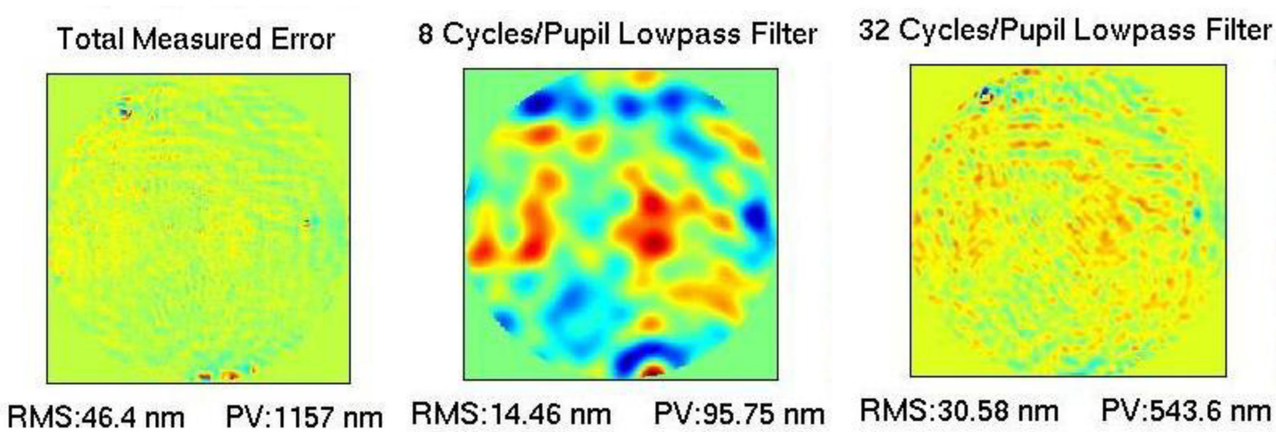

Figure 6 MGS phase retrieval results showing total residual WFE after control, and residual WFE broken down into error in the controllable passband of each deformable mirror.

3.3 Operations

PALM-3000 is intended to be a facility system for Palomar Observatory. The system has now been installed at Cass eleven times, eight of which were performed completely by the Palomar staff. As of June 2012, the system is being operated for science observations by Palomar staff with occasional support from JPL for technical issues.

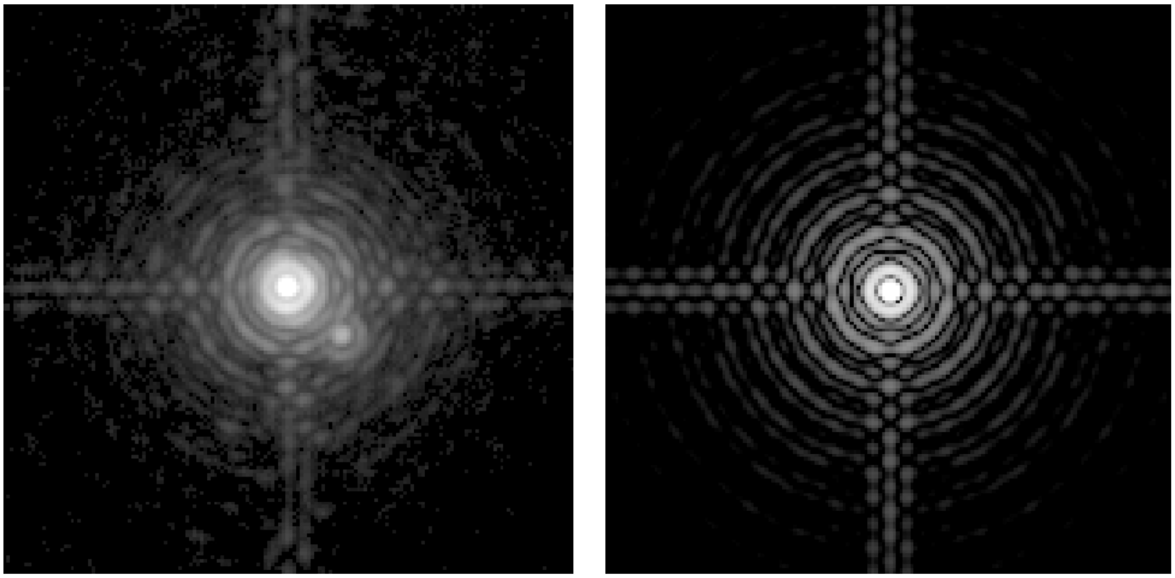

Figure 7 0.52” seeing (visible); 64.6% BrGamma Strehl on mv=0.0 (Vega), 2.2min total integration (96 frames); Perfect PHARO BrGamma PSF (ND filter ghost not shown, but accounted for in Strehl calculations)

4. TESTING AND FUTURE IMPROVEMENTS

Work is continuing on improving the system in order to achieve the performance goals. The 32x and 8x pupil-sampling modes have been implemented in the RTC and are being tested in the lab. Improved reconstructors are being tested on the sky.

4.1 Servo Control Testing and Optimization

The primary thrust of the continuing work on the system is in optimizing the servo control. This involves work on optimal reconstructors as well as optimal spatial splits between the deformable mirrors and use of offloading between mirrors. A simple Simulink model is being developed to test the reconstructors. Testing is also ongoing both in the lab and on the sky.

System bandwidth is also being testing in the lab. Initial testing does not show any issues with latency in the system, but more detailed investigation is necessary.

4.2 Additional functionality

The primary functionality included in error budget assumptions, but not yet implemented in the system is an anti-aliasing filter in the Shack-Hartmann WFS. The hardware to implement this upgrade is already installed. Operating the Shack-Hartmann in with the anti-aliasing filter also requires modifications to the centroiding algorithms in order to maintain a stable closed loop. This additional centroiding functionality will be implemented in summer 2012. Testing the anti-aliasing filter is planned for later in the year.

5. CONCLUSIONS

PALM-3000 is a high-contrast upgrade to the AO system at Palomar Observatory. It is currently being used on the sky for shared risk science with performance results that are slightly lower than the performance predicted by the error budget. Even at the current performance levels, there is useful science data being taken. With continued optimization, we expect to improve performance to the predicted levels and with the addition of the 32x and 8x modes, a broader range of observations will be possible, making PALM-3000 a critical instrument for science at Palomar Observatory.

ACKNOWLEDGMENTS

This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

This work was also supported by National Science Foundation grant AST-0619922, PI: Dr. R. Dekany. Support for the wavefront reconstructor computer has been provided by the Air Force Office of Sponsored Research, Award #FA9550-06-1-0343 (DURIP FY06). Support for the PALM-3000 3388 actuator DM was provided by a NASA Small Business Innovation Research grant #NNG06CA21C.

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